Roaring back. The Tevatron (far ring) is finally producing data at a copious rate.

HIGH-ENERGY PHYSICS

Aging Atom Smasher Runs All Out In Race for Most Coveted Particle

After years of frustration, Fermilab's Tevatron collider is running well. Researchers say they have a shot at spotting the Higgs boson—if there's time

In autumn 2004, Boston's beloved baseball team, the Red Sox, spotted the archrival New York Yankees a three-games-to-none lead in the best-of-seven American League Championship Series. The plucky Sox then whipped the Yankees in four straight and went on to win the World Series for the first time in 86 years. Now, physicists at Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, hope to pull off a similarly dramatic comeback and bag particle physics' biggest prize, the long-sought Higgs boson.

Four years ago, physicists wrung their hands as Fermilab's Tevatron collider faltered after a major upgrade (*Science*, 8 February 2002, p. 942). The revamped machine failed to smash protons into antiprotons at the rate researchers had counted on. As a result, many thought the 6-kilometer-long Tevatron had no chance of making a major discovery before a more powerful particle smasher—the 27-kilometer-long Large Hadron Collider (LHC) under construction at the European particle physics laboratory, CERN, near Geneva, Switzerland—came to life, as it is supposed to do next year.

But after a reshuffling of personnel and much hard work, the Tevatron is now cranking out data at a prodigious rate. And experimenters at Fermilab are cautiously optimistic that, if nature cooperates, they have a shot at seeing the Higgs boson, the particle thought to give other particles their mass. The Tevatron hasn't recovered completely from its missteps; if the machine continues to improve, by 2009 it will produce slightly more than half the data researchers once hoped for. But that may be just enough to spot the Higgs.

"Two or three years ago, we couldn't foresee having enough data to have a fair chance," says Jacobo Konigsberg, an experimenter at the University of Florida, Gainesville, and co-spokesperson for CDF, one of two large particle-detector experiments fed by the Tevatron. "Now the picture has changed tremendously." If the Higgs is light, no more than about 130 times as massive as a proton, then Fermilab researchers might be able to spot it, says Gerald Blazey, an experimenter at Northern Illinois University in Dekalb and co-spokesperson for DZero, the other particle-detector experiment.

That's if the Tevatron runs through 2009 as planned. The U.S. Department of Energy (DOE) could unplug the machine a year earlier to free up money for future projects—in particular, the proposed International Linear Collider, a 30-kilometer-long straight-shot behemoth that would map the conceptual terrain opened by the LHC (*Science*, 21 February 2003, p. 1171). In a year, a DOE advisory panel will evaluate the Tevatron's performance and recommend whether to shutter it early. "They've turned that machine around remarkably," says Lyn Evans, a physicist at CERN, who is directing construction of the LHC. "It's a tough call whether to run the Tevatron in 2009, that's for sure."

High expectations and low luminosity

To make a comeback, first you have to fall behind. And that's what the Tevatron did in 2001, when it started up after a 5-year overhaul in which physicists replaced the accelerator that feeds the collider protons and antiprotons. Experimenters had hoped the Tevatron would pump out collisions 10 to 20 times faster than it had before the upgrade. But 2 years into "Run II," it was producing collisions at only twice the previous rate. To spot the Higgs, experimenters needed a torrent of data. They got a trickle.

The key problems lay not with the new main injector but with the system to produce antiprotons, says Roger Dixon, head of the accelerator division at Fermilab. To generate antiprotons, the machine fires protons into a metal target, and an accelerator known as the accumulator collects the bits of antimatter that result. Physicists had hoped to pass the particles into yet another accelerator known as the recycler to cool them and pack them into tight bunches before passing them to the main injector and into the Tevatron. But the recycler wouldn't cooperate, and accelerator physicists had to bypass it entirely.

Fermilab threw everything it had at the Tevatron and even called on other labs for help. Then-director Michael Witherell shook up the lab's accelerator division. In 2003, the new management set a timetable for improving various parts of the facility and increasing the rate at which the Tevatron produces collisions, a quantity that is known as the luminosity and is measured in inverse femtobarns. Since then, researchers have stayed on schedule, says Fermilab accelerator physicist David McGinnis. In June 2004, they brought the recycler on line and last August implemented a bold scheme to cool antiprotons in it with electrons. The Tevatron now produces as much data in 6 weeks as it did in all of Run I, from 1992 through 1996.

In retrospect, some of the angst over the Tevatron's performance early in Run II stemmed from unrealistic expectations, some say. "Everyone in the trenches knew this was going to be a marathon, not a sprint, and that it was going to be slow going at the start," McGinnis says. "I don't think that message got through to the experimenters." The Tevatron is on pace to log a total of 8 inverse femtobarns by the end of 2009, maybe just enough to snare the Higgs, the linchpin of the standard model of particle physics.

Whence mass?

The standard model marries the electromagnetic force, which accounts for all of electricity and magnetism, and the weak nuclear force, which produces a kind of radioactive decay. Since the 1970s, physicists have known that the two are different manifestations of the same thing,

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although they aren't exactly interchangeable. The electromagnetic force works at lengths as long as lightning; the weak force reaches only across an atomic nucleus. That's because the photons that convey the electromagnetic force are massless particles, whereas the particles that carry the weak force, the W and Z bosons, weigh far more than a proton.

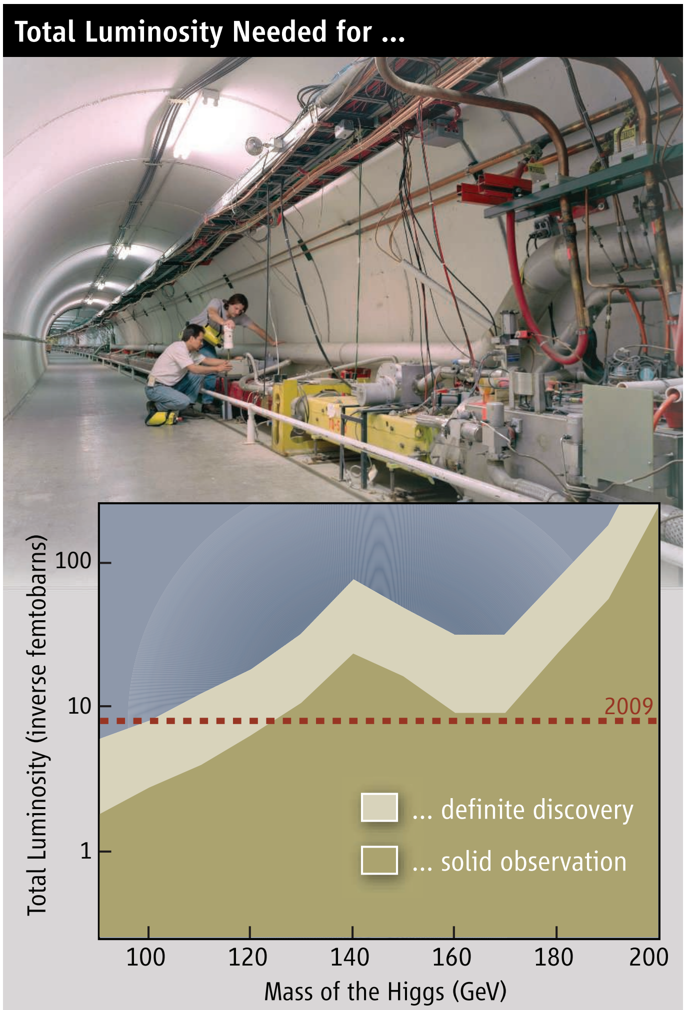
But there's a catch. If theorists simply assign masses to the W, Z, and other particles, the standard model goes haywire mathematically. To "break the symmetry" between the forces, mass must originate somehow through the interactions of particles that are otherwise massless themselves.

That's where the Higgs comes in. Theorists assume that empty space is filled with a Higgs field, which vaguely resembles an electric field. The field drags on other particles, giving them inertia or mass. Like all fields, the Higgs field consists of hidden "virtual" particles that can pop into existence in sufficiently violent collisions.

The standard model does not predict the mass of the Higgs, but the theory is so tightly interconnected that precise measurements of familiar particles limit the possibilities. Measurements of the mass of the W, the mass of a particle called the top quark, and other particle properties suggest that the Higgs is light and possibly within the Tevatron's grasp, says Volker Buescher, a member of the DZero team from the University of Freiburg in Germany. Physicists measure masses and energies in electron volts; the Tevatron smashes particles with an energy of 1.96 trillion electron volts, or TeV. That's enough to generate new particles with masses of a few hundred billion electron volts, or GeV.

However, the standard model also enables physicists to estimate how often a Higgs of a particular mass will emerge and how hard it will be to detect as it decays into other particles. With those effects taken into account, the Tevatron should be able to unearth evidence of the Higgs if the particle's mass is less than 125 GeV. "While a Higgs search up to 125 GeV may sound limited, that's exactly the range where we would expect to find it," Buescher says. With 8 inverse femtobarns of data, researchers should be able to spot solid evidence, if not incontrovertible proof, of a Higgs in that range—if it's there.

Of course, the standard model explains "electroweak symmetry breaking" in only the simplest and most ad hoc way. Nature could play by richer and more complicated rules. For example, a theory called supersymmetry posits an undiscovered "superpartner" for every known particle. The theory helps solve conceptual problems with the standard model, and it requires at least two Higgs fields and five Higgs particles, the lightest of which resembles the standard model Higgs. That particle might be harder to find, says Marcela Carena, a theorist at Fermilab. On the other hand, measurements at the Tevatron may significantly limit the parameters of supersymmetry. "One way or the other," Carena says, "the Tevatron will shape our understanding of physics beyond the standard model in the next 2 or 3 years."



Just enough? The Tevatron could pump out 8 inverse femtobarns of data by the end of 2009. That should allow researchers to glimpse the Higgs boson if its mass is less than roughly 125 GeV, as other data suggest.

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An early exit?

All of this depends on the Tevatron's logging as much data as possible. But researchers would get at most 6 inverse femtobarns of luminosity if the Tevatron shuts down at the end of 2008. DOE's Particle Physics Project Prioritization Panel (P5) will weigh several factors next spring when considering whether to stop the machine early, says panel chair Abraham Seiden of the University of California, Santa Cruz.

Most important will be the performance of the Tevatron and its CDF and DZero detectors. Experimenters say the detectors are running in top form, and accelerator physicists are just now completing the last upgrades that should get the Tevatron to a full 8 inverse femtobarns. But even if all the machinery runs perfectly, Fermilab faces a problem: Half of all experimenters may leave for the LHC by 2009. Having studied the issue, Fermilab officials are confident they can keep the experiments running, says Fermilab experimenter Joel Butler. "The real issue is can the data be analyzed in a timely fashion? Because of the LHC, it has a shelf life," he says. But even on that account, he's optimistic: "If there is a real shot to get the Higgs, people will stay to do the analysis."

P5 will also consider progress on the LHC, which should turn on next autumn and take its first data the following spring. The LHC, which will crash protons into protons at a whopping 14 TeV, will come on slowly, says CERN's Evans. That's because it will pack so many protons and so much energy into its beams that should a beam accidentally strike the accelerator itself, it could blast a crippling hole in it. "The speed with which we bring up the luminosity will be limited by our ability to protect the machine," Evans says. But, he adds, "certainly in 2009 we'll be up to 50% of luminosity and completely swamping the Tevatron."

Ultimately, whether the Tevatron runs through 2009 may depend on whether researchers catch a whiff of something in the next year, Seiden says. "The main thing will be the Tevatron data itself," he says. "If it looks interesting, that's a really important plus. If it looks unlikely [to yield a discovery], you might want to think of ending earlier."

Only time will tell what nature has in store. So for the moment, physicists at Fermilab continue to push to improve the performance of the Tevatron and their detectors. In the competition for the Higgs, they've entered the late innings and are down a couple of runs—or inverse femtobarns. But they can feel their fortunes turning and hope for one last shot at triumph. As they say in baseball, it's not over till it's over.

–ADRIAN CHO